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SEP 81 J R WARD, T L BROSSEAU, B B GROLLMAN

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HEAT TRANSFER IN GUNS - DETERMINATION OF FRICTION FACTOR FROM HEAT INPUT MEASUREMENTS

J. Richard Ward
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September 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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Nordheim's method, from the 1940s, uses the Reynolds analogy between heat transfer and momentum transfer to estimate a convective heat transfer coefficient Only the Fanning friction factor must be determined experimentally.

Friction factors were determined for three 155mm propelling charges (M119, XM201, and XM203E2, the latter two minus wear-reducing additive) from measured heat input data. The reciprocal friction factor for the three charges was 335, 365, and 400, respectively, in contrast to a value of 323 Nordheim used

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20. ABSTRACT (Continued)

from World War II data. The friction factor for the 105mm M467 cartridge was also determined for which the reciprocal friction factor was 334 vs 299 using Nordheim's constants for a 105mm gun.

In instances where measured heat inputs are unavailable, the friction factor, λ, can be estimated for a gun with diameter, D, by

$$\lambda = (a + 4 \log_{10} D)^{-2} ,$$

where a = 14.3 and the diameter in centimeters. Nordheim recommended a value of 13.2.

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I. INTRODUCTION

An extensive investigation of gun barrel wear and its control in hypervelocity guns was sponsored by the National Defense Research Committee during World War II.[1] A key element in that investigation was a technique to compute heat transfer to the gun barrel wall from the hot, propellant combustion gases. An interior ballistics scheme by Nordheim and coworkers at Duke University[2] used the Reynolds analogy between heat transfer and momentum transfer to obtain a convective heat transfer coefficient.

$$h = \tfrac{1}{2} \lambda C_p \rho V , \tag{1}$$

where h = heat transfer coefficient,

λ = friction factor,

C_p = specific heat of combustion gases,

ρ = density of combustion gases, and

V = velocity of combustion gases.

Nordheim noted that the Reynolds analogy produced a heat transfer coefficient in which the friction factor was the only quantity to be deduced from the interior ballistics. Nordheim also showed how the friction factor could be determined experimentally with fast-response thermocouples welded near the bore surface. Nordheim used heat input from a machine gun to set constants for friction factor estimation.

Hobstetter used Nordheim's method to estimate the minimum chromium plate thickness to protect the underlying steel from a martinsitic phase change,[3] and later workers used the method for empirical wear models.[4,5]

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[1] *"Hypervelocity Guns and the Control of Gun Erosion," Summary Technical Report of Division 1, National Defense Research Committee, Wash. D.C., 1946.*

[2] *L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, March 1944.*

[3] *J.N. Hobstetter, "Application of Heat Transfer Theory to Metallographic Evidences of Gun Erosion," NDRC Armor and Ordnance Report No. A-452, December 1945.*

[4] *R.N. Jones and P.S. Breitbart, "A Thermal Theory for Erosion of Guns by Powder Gases," Ballistic Research Laboratory Report No. 747, January 1951.* (AD #801741)

[5] *C.S. Smith and J.S. O'Brasky, "A Procedure for Gun Barrel Erosion Life Estimation," Proceedings of the Tri-Service Symposium on Gun Tube Wear and Erosion, ADPA, Dover, NJ, March 1977.*

The heat input measurements Nordheim advocated have been in use the past several years to assess wear-reducing liners,[6] but not yet to compute friction factors. In this report heat transfer data from a 105mm M68 tank gun[7] and a 155mm M185 howitzer[8] are used to compute friction factors. These friction factors are then compared to Nordheim's values as well as test Nordheim's assumption that the friction factor depends only on bore diameter.

II. DETERMINATION OF FRICTION FACTOR

Nordheim's procedure for computing heat inputs will be taken directly from his report[2]; the original report should be consulted for more detail. A plot of heat input vs friction factor will be created for each charge; the friction factor corresponding to the experimental heat input can then be determined from the plot.

Propellant properties were determined with the BLAKE thermochemical code;[9] other interior ballistic parameters were available in Heppner's report.[10]

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[6] *J.A. Lannon and J.R. Ward, "Workshop Report on the Mechanisms of Wear-Reducing Additives in Reducing Erosion," Proceedings of the 17th JANNAF Combustion Meeting, Langley AFB, September 1980.*

[7] *T.L. Brosseau and J.R. Ward, "Measurement of Heat Input into the 105mm M68 Tank Cannon Firing Rounds Equipped with Wear-Reducing Additives," Ballistic Research Laboratory Technical Report No. 02056, April 1978.* (AD #A056368)

[8] *J.R. Ward and T.L. Brosseau, "Effect of Wear-Reducing Additives on Heat Transfer into the 155mm M185 Cannon, Ballistic Research Laboratory Memorandum Report No. 2730, February 1977.* (AD #A037374)

[9] *E. Freedman, "BLAKE-A Ballistic Thermodynamic Code Based on TIGER," Proceedings of the International Symposium on Gun Propellants, October 1973.*

[10] *L.D. Heppner, "Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunitions," Report No. APG-MT-4503, September 1974.*

Step one in determining the heat input is to define a heating parameter,

$$L = 43.1 \cdot \frac{\lambda \cdot C_p}{(kc\rho_s)^{1/2}} \cdot \frac{C^{3/4}}{m^{1/4} A^{1/2} F} \cdot \left(\frac{1 - \Delta/\rho_p}{\Delta}\right)^{3/4} \cdot P_{max}^{5/4} \quad , \qquad (2)$$

where previously undefined parameters are

k = thermal conductivity of steel,

c = specific heat of steel,

ρ_s = density of steel,

C = charge weight,

m = reduced projectile mass,

A = cross-section area of barrel,

F = impetus of propellant,

Δ = loading density,

ρ_p = propellant density, and

P_{max} = maximum chamber pressure.

All quantities are defined by the interior ballistic inputs or the physical properties of steel except λ and m.
These quantities are defined below:

$$\lambda = (a + 4 \log_{10} D)^{-2} \quad , \qquad (3)$$

where D = bore diameter, cm, and

$$m = 1.04 \, (m_o + C/3) \quad , \qquad (4)$$

where m_o = projectile mass.

Nordheim estimated a = 13.2 from World War II data; in the calculations here, trial values of λ will be selected in order to find the value of λ that matches the experimental heat input from references 7 and 8.

Step two is to define a reduced time coefficient,

$$\alpha = \frac{\left[\frac{C(1-\Delta/\rho p)}{\Delta \cdot m} \cdot 3.45\ P_{max}\right]^{\frac{1}{2}}}{0.18 \cdot U_o(1-\Delta/\rho_p)} \cdot A \quad . \tag{5}$$

The reduced time coefficient is used to get a nondimensionalized time,

$$\tau = \alpha t, \tag{6}$$

where t = time after propellant ignition.

Of particular interest here will be τ_b, the time when propellant is totally burned. For all the calculations in this report, $\tau_b = 24$, so that the tables Nordheim provides can be used to relate interior ballistic parameters to heat input.

Step three is to determine the axial location where the heat input is measured. Axial distance in Nordheim's notation is

$$X_s = U_s/A \quad , \tag{7}$$

where X_s = coordinate of a specific location, s, and

U_s = volume of gun up to point, s.

The reduced length, Y_s, is defined as

$$Y_s = X_s - C/(A \cdot \rho_p) \quad . \tag{8}$$

The reduced length, Y_o, refers to the beginning of projectile travel; experimental heat inputs were taken when $Y_s/Y_o = 1.2$.

The final item needed to compute total heat input is the heat transfer integral, I. For $\tau_b = 24$ and $Y_s/Y_o = 1.2$, the functional dependence of I vs L was computed by Nordheim for a propellant with initial temperature of 300K and a 2,700K flame temperature as shown in Figure 1. If the flame temperature or the initial temperature differ from the nominal values, then the heat transfer integral becomes

$$I_\infty = \left(\frac{T_o}{2,500}\right) I - \left[\theta_o - 300\left(1 - \frac{T_o}{2,500}\right)\right] S \quad , \tag{9}$$

where T_o = adiabatic flame temperature,

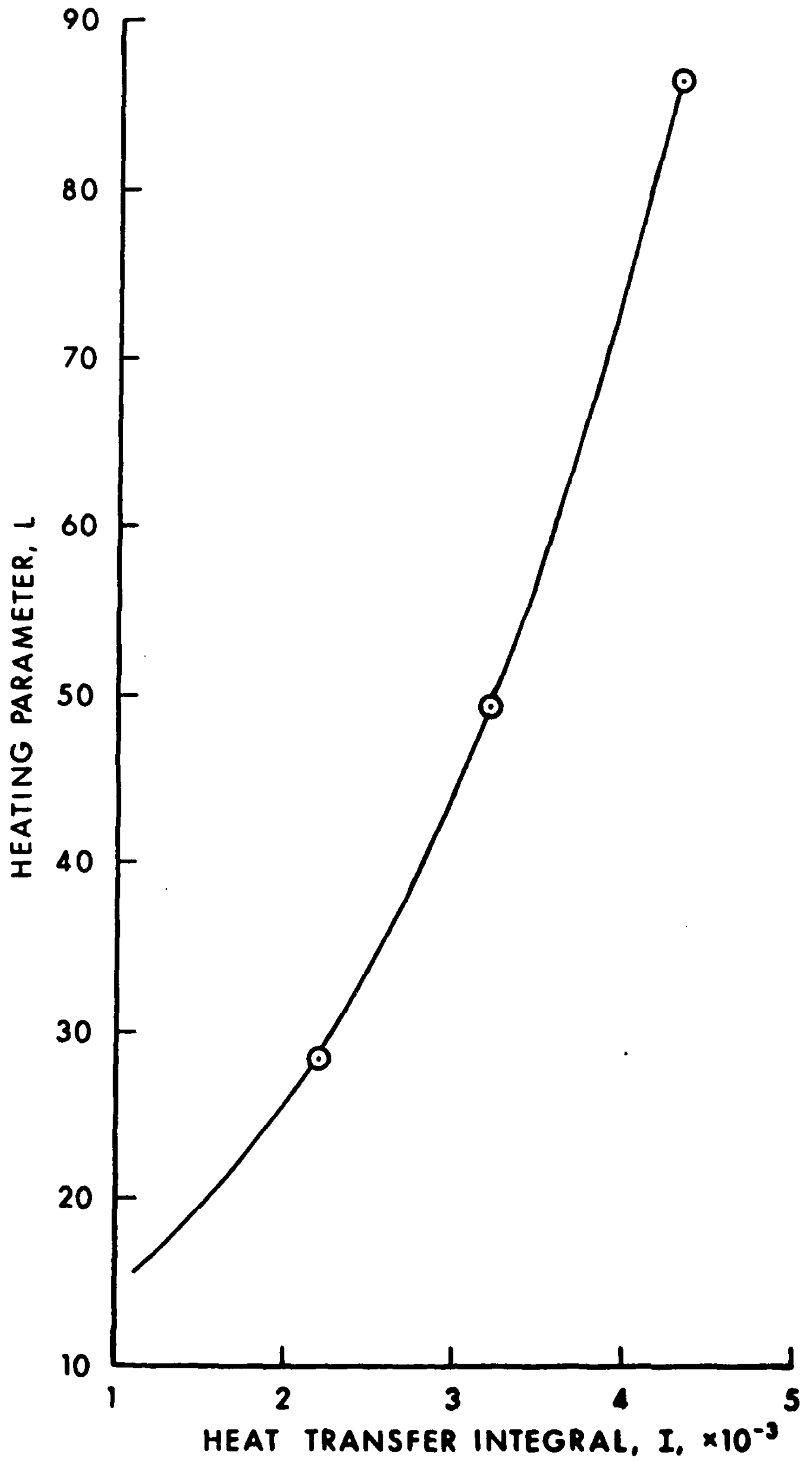

Figure 1. L vs I for τ_b = 24 and Y_s/Y_0 = 1.2

θ_o = initial propellant temperature, and

S = a function of L.

Nordheim also computed L vs S for τ_b = 24 and Y_s/Y_o = 1.2 as shown in Figure 2.

The total heat input, Q_∞, is then

$$Q_\infty = \frac{{}^2\rho_s fk^{\frac{1}{2}}}{\alpha} \cdot I_\infty \quad . \tag{10}$$

To recapitulate, heat input at given J_b and Y_s/Y_o is calculated by the following steps:

1. for a given value of λ, compute L with Eq. (2),

2. take values of I and S from Figures 1 and 2 for the given value of L,

3. compute I_∞ with Eq. (9), and

4. compute Q with Eq. (10).

The appropriate propellant properties and interior ballistic parameters are given in Tables 1 and 2. Nordheim gives the physical properties for gun steel as

$$(\rho_s ck)^{-\frac{1}{2}} = 2.8 \frac{cm^2 \cdot s^{\frac{1}{2}}}{cal} \quad , \text{ or} \tag{11}$$

$$(\rho_s ck)^{-\frac{1}{2}} = 67 \times 10^{-6} \frac{m^2 s^{\frac{1}{2}}}{J} \quad . \tag{12}$$

III. RESULTS AND DISCUSSION

Figures 3-6 depict heat input vs friction factor for the four propelling charges considered.

Table 3 summarizes the friction factors determined with the experimental value of heat input along with the friction factor Nordheim recommended from World War II data. One can see Nordheim's friction factors overestimate the measured heat input in both the 105mm and 155mm guns. One also notes three 155mm charges give different friction factors belying Nordheim's assumption that the friction factor depends solely on bore diameter. Hence, one should use measured heat input to obtain a friction factor prior to using Nordheim's scheme to compute bore surface temperature as a function of time or to compute temperature vs time in the barrel wall.

Since it is desirable to be able to estimate heat input or bore surface temperatures when measured heat inputs are unavailable, it was decided to assume the friction factors were dependent on diameter and see what error in

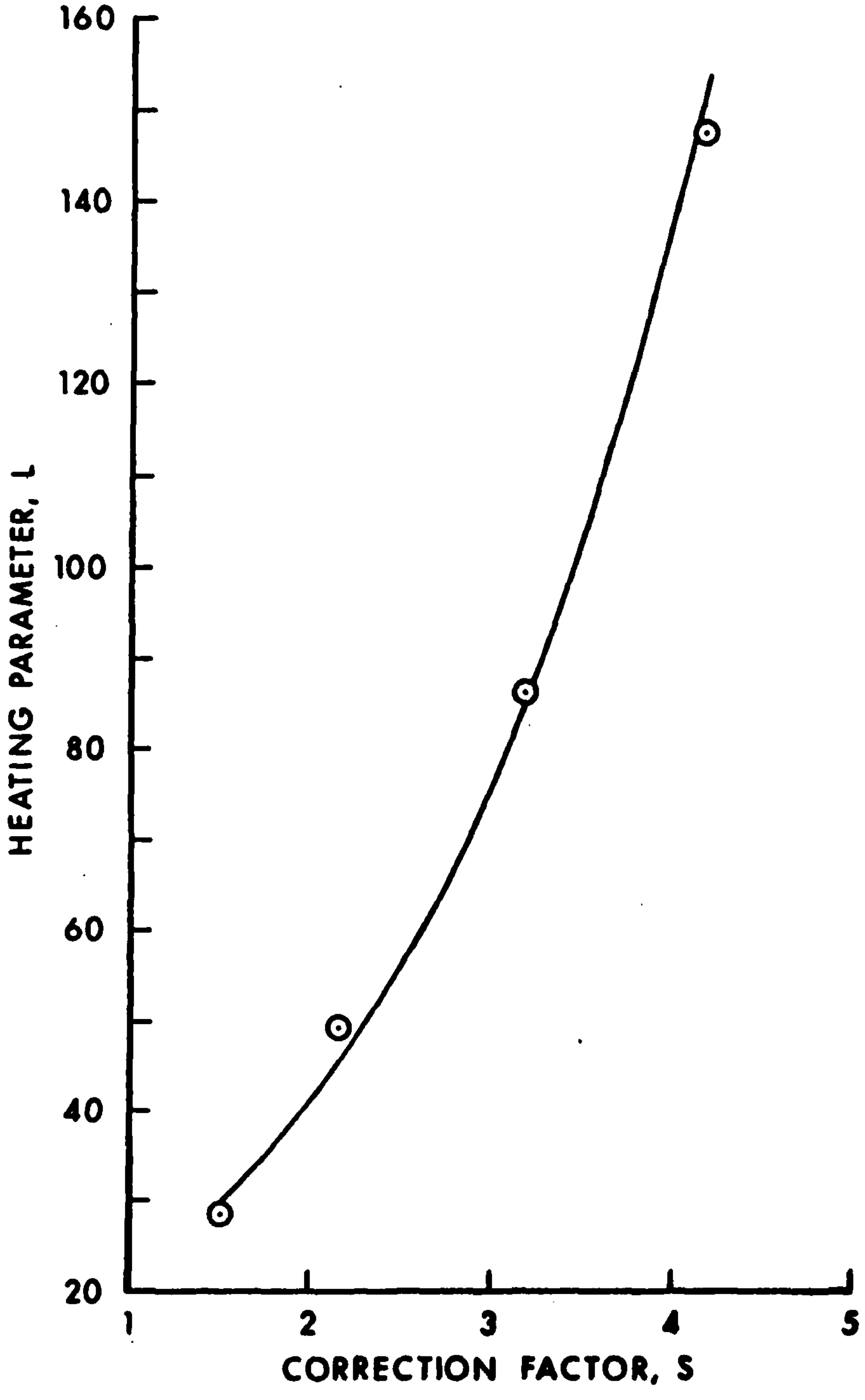

Figure 2. Functional Dependence of L vs S

TABLE 1. PROPELLANT PROPERTIES FOR HEAT TRANSFER CALCULATIONS

	M1	M6	M30A1
T_o, K, x 10^{-3}	2.48	2.60	3.00
Cp, J/kg-K, x 10^{-3}	1.82	1.84	1.88
F, J/kg, x 10^{-6}	0.928	0.955	1.065
ρ_p, kg/m^3, x 10^{-3}	1.6	1.6	1.67

TABLE 2. INTERIOR BALLISTIC PARAMETERS FOR PROPELLING CHARGES OR CARTRIDGE

	XM203E2	XM201	M119	M467
Gun	M185	M185	M185	M68
Propellant	M30A1	M30A1	M6	M1
Projectile	M549	M107	M107	M468TP-T
U_o, m^3, x 10^2	1.88	1.88	1.88	0.675
C, kg	11.9	7.89	9.23	2.74
m_o, kg	43.5	43.1	43.1	11.2
m, kg	49.4	47.6	48.0	12.6
A, m^2, x 10^2	1.92	1.92	1.92	0.893
P_{max}, Pa, x 10^{-8}	3.28	2.07	2.06	1.70
α, s^{-1}, x 10^{-3}	4.75	3.49	3.61	4.74
Δ, kg/m^3, x 10^{-2}	6.3	4.2	4.9	4.1

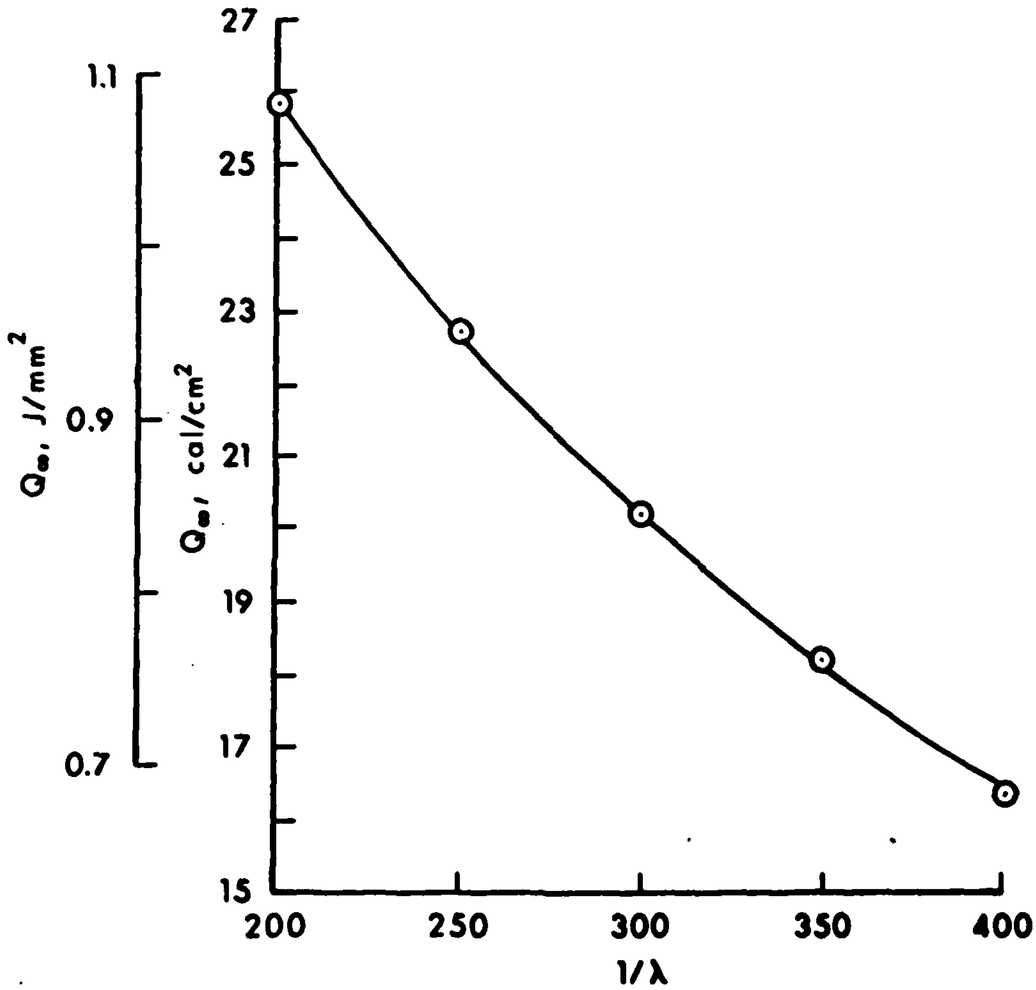

Figure 3. Heat Input *vs* Friction Factor for M467 Cartridge

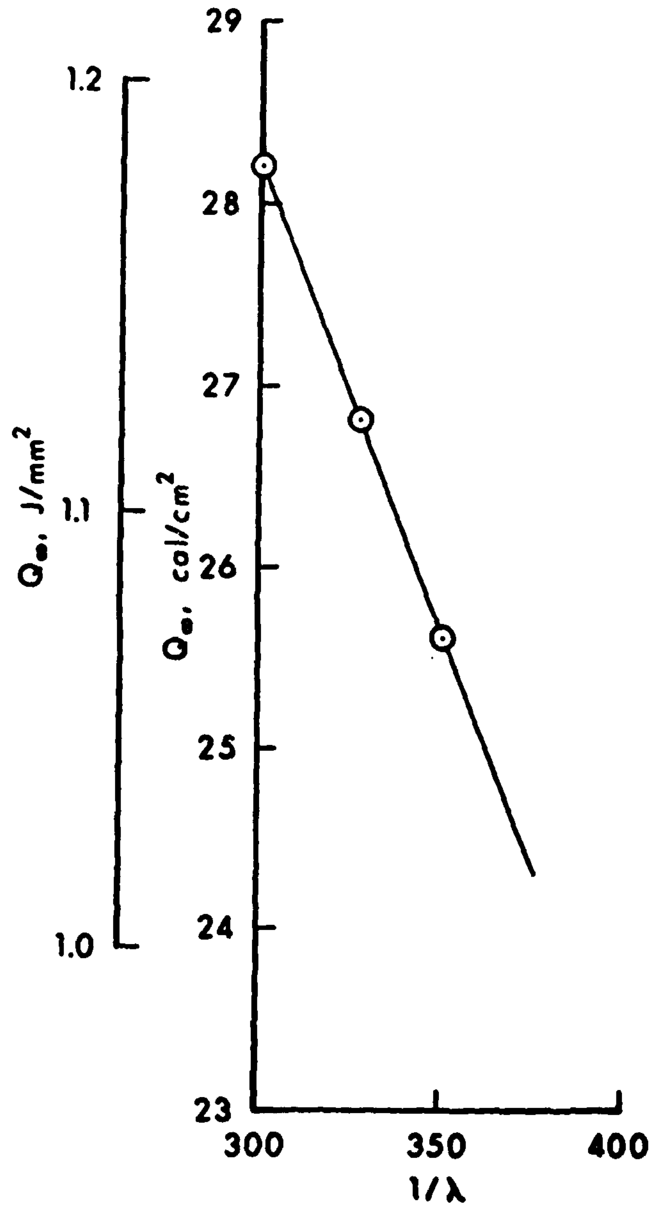

Figure 4. Heat Input vs Friction Factor for M119 Charge

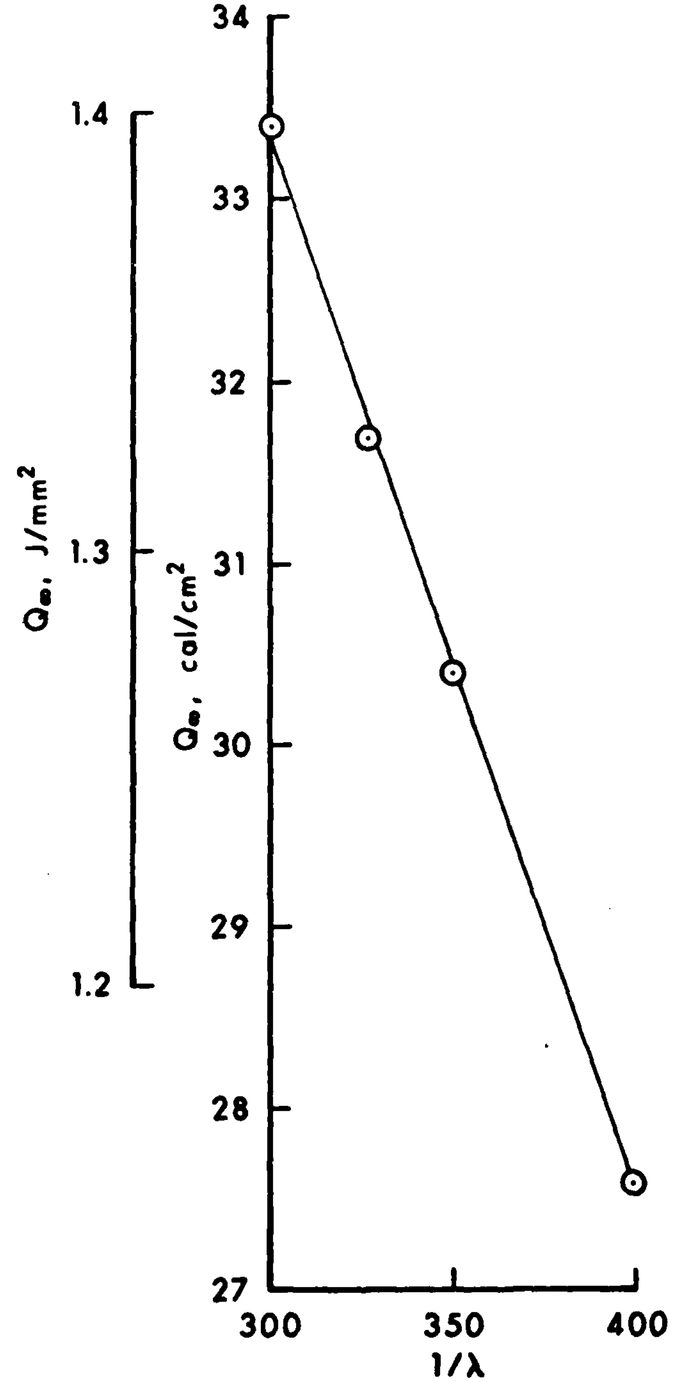

Figure 5. Heat Input vs Friction Factor for XM201 Charge (No Additive)

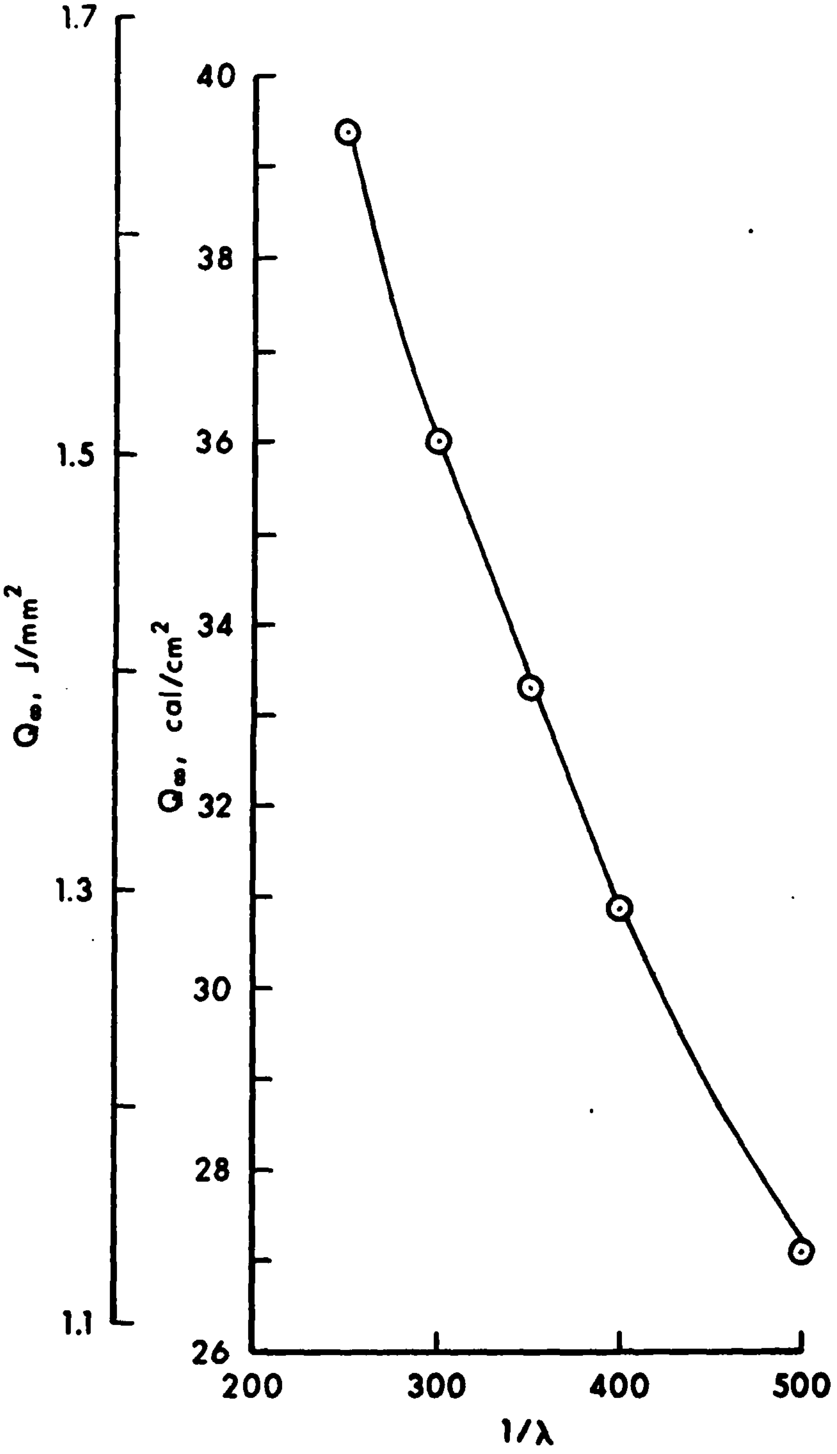

Figure 6. Heat Input vs Friction Factor for XM203E2 Charge (No Additive)

TABLE 3. FRICTION FACTORS FROM EXPERIMENTAL HEAT INPUTS

Charge	$Q, J/mm^2$, expt'l, (cal/cm^2)	$1/\lambda$, expt'l	$1/\lambda$, Eq. (3)	$Q, J/mm^2$, cal'd, (cal/cm^2)
M467	0.782 (18.7)*	334	299	0.845 (20.2)
M119	1.10 (26.4)**	335	323	1.13 (27.0)
XM201, no additive	1.24 (29.6)**	365	323	1.34 (32.0)
XM203E2, no additive	1.29 (30.9)**	400	323	1.45 (34.7)

*Reference 7
**Reference 8

total heat input was introduced by this assumption.

To estimate the diameter dependence, Eq. (3) is rearranged with s expressed as the dependent variable to give

$$s = (1/\lambda)^{\frac{1}{2}} - 4\log_{10}D \quad . \tag{13}$$

Table 4 summarizes the values of s determined from the friction factors computed from measured heat inputs in the 155mm and 105mm guns.

TABLE 4. DIAMETER DEPENDENCE OF FRICTION FACTOR

Charge	$1/\lambda$	D,cm	s
M467	334	10.5	14.2
M119	335	15.5	13.5
XM201, no additive	365	15.5	14.3
XM203E2, no additive	400	15.5	15.2

The mean value and sample standard deviation for the three 155mm charges are 14.3 ± 0.8 in comparison to the value of 14.2 for the M467 cartridge. These limited results suggest that one use a value of 14.3 in Eq. (3) to obtain friction factors in the absence of any experimental heat inputs rather than Nordheim's value of 13.2. Table 5 compares heat inputs computed with 14.3 and 13.2 in Eq. (3) with the experimental heat inputs.

IV. CONCLUSIONS

1. Friction factors were determined for the 155mm M119, XM201, and XM203E2 propelling charges and the 105mm M467 cartridge from experimental heat inputs. These friction factors were smaller than those Nordheim estimated from World War II heat input data; heat inputs computed with Norheim's method overestimate actual heat inputs.

2. The friction factors for the 155mm charges were not independent of bore diameter as required by Nordheim's model of heat transfer. This means the physical significance Nordheim attached to the friction factor is questionable.

3. In instances where experimental heat inputs are unavailable, better estimates of the friction factor can be made using a value of 14.3 in Eq. (3) rather than 13.2 as recommended by Nordheim from World War II data.

TABLE 5. COMPARISON OF EXPERIMENTAL AND COMPUTED HEAT INPUTS ASSUMING FRICTION FACTOR DEPENDENT ONLY ON BORE DIAMETER

Charge	Q,J/mm^2, expt'l (cal/cm^2)	Q,J/mm^2, cal'd (cal/cm^2)*	Q,J/mm, cal'd (cal/cm^2)**
M119	1.10 (26.4)	1.03 (24.7)	1.13 (27.0)
XM201, no additive	1.24 (29.6)	1.23 (29.5)	1.34 (32.0)
XM203E2, no additive	1.29 (30.9)	1.31 (31.4)	1.45 (34.7)

*Calculated with 14.3 in Eq. (3) to obtain λ.
**Calculated with 13.2 in Eq. (3) to obtain λ.

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1. "Hypervelocity Guns and the Control of Gun Erosion," Summary Technical Report of Division 1, National Defense Research Committee, Wash. D.C., 1946.

2. L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, March 1944.

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Please take a few minutes to answer the questions below; tear out this sheet, fold as indicated, staple or tape closed, and place in the mail. Your comments will provide us with information for improving future reports.

1. BRL Report Number ________________________

2. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which report will be used.)

3. How, specifically, is the report being used? (Information source, design data or procedure, management procedure, source of ideas, etc.)

4. Has the information in this report led to any quantitative savings as far as man-hours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

5. General Comments (Indicate what you think should be changed to make this report and future reports of this type more responsive to your needs, more usable, improve readability, etc.)

6. If you would like to be contacted by the personnel who prepared this report to raise specific questions or discuss the topic, please fill in the following information.

Name:

Telephone Number:

Organization Address: